ROLE OF VOLATILES IN A TIDAL DISRUPTION OF ICE RICH BODIES.
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Abstract. This paper suggests a new mechanism of tidal disruption of comets and volatile-rich planetesimals passing planets within the Roche limit. I suggest that these bodies could be disrupted not only by the tidal force itself, but by the pressure released in shear layers along discontinuities associated with failures in the interior of stray bodies. The heat released in the shear layers can be sufficient for the evaporation of highly volatile materials; the resulting pressure can disrupt the comets or ice-rich planetesimals in the outer parts of the early solar system.

Energy dissipation in a zone of discontinuous displacement. The failure of a solid body subjected to tidal perturbations is usually considered by approximating the body either as a homogeneous elastic or a viscous sphere. A stray sphere of inviscid fluid is tidally disrupted if its pericenter distance is less than 1.05 $(M/\rho)^{1/3}$, where M is the mass of the planet, and ρ is the density of the stray body [1]. Highly viscous bodies may not be disrupted at all [2]. To estimate the intensity of heating in the shear layer, let us assume that the comet failed in its central part by the shear. (The failure may spread through the whole body or be confined in the inner part of it, with the two halves sliding back and forth with respect to one another till the energy of oscillation is dissipated in the shear layer.) We will approximate the shear layer as a viscous fluid and assume that the released vapor does not escape from the comet. Then the rate of the dissipation of energy (per unit mass) can be estimated as $dE/dt = \nu\, (\partial V/\partial y)^2$.

The amount of thermal energy released in the shear layer can be expressed in terms of the total displacement of opposite sides of the shear layer ($\delta R_d \sim \int V\, dt$). It is given by

$$\Delta E = \frac{S_{yx}}{\rho_c}\frac{\delta R_d}{\Delta y} = \Delta E \sim 2\times 10^8 \frac{\delta R_d}{R_c}\left(\frac{M_c}{4\times 10^{15}\,\mathrm{g}}\right)\left(\frac{\rho}{1\ \mathrm{g\ cm^{-3}}}\right)^{-1}\left(\frac{\Delta y}{1\ \mathrm{cm}}\right)^{-1} \mathrm{erg\ g^{-1}} \qquad (1)$$

where Δy is the thickness of the shear layer.

Discontinuous displacements in solids could be paper-thin. The lower limit for the Δy is determined by the thermal conductivity in the shear layer spreading of the heat over $\Delta y_T \sim \sqrt{\kappa\, t}$, where t is the timescale of the displacement of halves of the body for δR_d. Assuming that $\delta R_d \sim R_c \sim V\, t \sim S_{xy}\, t^2/(\Delta y\, \rho)$, and substituting $\Delta y = \Delta y_T \sim \sqrt{\kappa\, t}$, gives $t \sim \kappa^{1/3}\, (\delta R_d\, \rho/S_{xy})^{2/3} \sim 5\, \rho^{2/3}$ s, and $\Delta y \sim \kappa^{2/3}(\delta R_d\, \rho/S_{xy})^{1/3} \approx 1$ cm. For this numerical estimation, the following values were used: $\delta R \sim 10^5$ cm, $S_{xy} \sim S' \sim 10^3$ erg cm^{-3}, $\rho \sim 1$ g cm^{-3}, and $\kappa = 10^{-1}$ cm^2 s^{-1}, which is a typical thermal conductivity for the crystalline ice between 50 and 100 K [3]. Greater thickness of the shear layer can be associated with its roughness. The radius of the body is assumed to be 1, 2, 4, or 8 km, and the density is between 0.5 and 1 g cm^{-3}. It is assumed that the body encounters Jupiter, and its trajectory is similar to that for the SL9 when it passed the planet within the Roche limit and was destroyed by its tides. It is assumed that no phase transition in the ice occurs before the temperature reaches sublimation point, and then the temperature is constant till evaporation is complete. Only after that can the temperature rise. It is taken also that the abundance of H_2O in the comet was 84.6%, CO - 10%, CO_2 - 3%, and H_2S, CH_4, and NH_3 - 0.2% each. (Other volatiles have not been taken into account.) In vacuum, the sublimation temperature of CO, CH_4, H_2S, CO_2, and H_2O are about 25, 31, 57, 72, and 152 K respectively [4]. The latent heats of sublimation are taken as 1.7×10^{10} erg g^{-1} for both CO and CO_2. This value is close to the maximal value for CO and CO_2 trapped in water ice [5]. The latent heat of evaporation of water is 2.6×10^{10} erg g^{-1}. For other volatiles, the latent heat is taken to be equal to 1×10^{10} erg g^{-1}. The calculations show that most of the CO is sublimated in all models well before the sliding halves of the comet are displaced by about R_c. This is correct even if the CO is dissolved in the matrix of amorphous ice, and if the sublimation occurs only when crystallization temperature of the water ice is reached. For bodies with a density of 1 g cm^{-3} and a radius of R_c = 1 km and 3 km, the release of CO is sublimated when the displacement is about 1, 0.15 R_c, respectively. In the latter case, all ices more volatile than H_2O are evaporated by the time the displacement approaches R_c. For a body with a radius of 4 km, the sublimation of CO and H_2O in the shear layer is complete when the displacement is <0.03 R_c and about 0.3 R_c provided that the thickness of the shear layer is ~1 cm, but CO is evaporated even if for this of larger bodies CO is sublimated even if the thickness of the shear layer is ~1 m. Hence, larger bodies have a greater chance of being disrupted than smaller ones with the same strength, despite gravitational pressure increasing with the size of the body. The disruption of stray bodies can take place even if the shear layer is remarkably wider than the thermal length-scale.

Disruption of the body by volatiles. To estimate the potential importance of released volatiles for the disruption of a stray body, let us assume that ξ is the mass fraction of the evaporated volatiles in the shear layer. In this case, the mass of the evaporated material $\Delta m = \xi\, \rho_c\, \Delta y\, S$, where S is the surface area of the shear layer. Let us assume that the vapor cannot escape from the volume element $\Delta V \equiv S\, \Delta y$. Then the density of the released gas is $\rho_\upsilon = \Delta m/\Delta V$, and it produces the pressure

$$P_{\upsilon 0} = \frac{k_T}{\mu m_H}\rho_\upsilon T_{e\upsilon} = \frac{k_T}{\mu m_H}\,\xi\,\frac{\rho_c \Delta y S}{\Delta V} T_{e\upsilon} \sim 10^8\,\xi\,\frac{\rho_c}{1\,\mathrm{g\,cm^{-3}}}\ \mathrm{erg\ cm^{-3}} \qquad (2)$$

where is k_T is the Boltzmann constant, $\mu\ m_H$ is the molecular weight, and $T_{e\upsilon}$ is the temperature of evaporation. If the shear layer percolates with N times larger volume, then $P_\upsilon = P_{\upsilon 0}/N$ provided that the vapor expands isothermally. Such an assumption is reasonable while $N < 10^2$, because in this case the work for the expansion of the vapor is less than latent heat evaporation. Therefore the expansion does not affect significantly the amount of volatile material that could be evaporated. For N ~ 1 one can see from the equation 2 that a body with a strength of ~ 10^3 erg cm^{-3} can be destroyed if $\xi \geq 10^{-4}$, i.e., the sublimation of even a small fraction of volatile materials can disrupt the comet or planetesimal. If $\xi \sim 10^{-1}$, i.e., if all the CO has evaporated in the closed volume of the shear layer, then a comet with a strength up to ~ 10^7 erg cm^{-3} can be disrupted. Note that the pressure of released vapors can likely disrupt the body into more than two fragments. The disruption is especially likely if the comet or planetesimal contains preexisting cracks or zones of weakness that may result from the formation process.

Summary.

This paper demonstrates that an internal release of volatiles might play a role in the disruption of ice-rich bodies—comets in the present and planetesimals in the early solar system. The release of volatiles might have been initiated by frictional heating in the shear layers along narrow failure zones. If the volatile ices are evaporated in a closed volume within the comet, their pressure could be sufficient to disrupt the body. The release of volatiles is most likely if the size of the body exceeded 2 to 3 km but weak enough to fail during the encounter. The release of volatiles in shear layers of zones of discontinuous displacements might have played a role in the tidal disruption of comets passing planets within Roche limit planets, and volatile-rich planetesimals encountering growing planets in the early solar system. Among the possible outcomes of the tidal disruption of stray bodies are phenomena observed when fragments of SL9 fell onto Jupiter. Tidal disruption of planetesimals in the early solar system can also affect the rate of the growth of the planet and the contamination of envelopes of giant planets with heavy elements.

References: [1] Sridhar S. and Tremaine S. (1992) *Icarus, 63,* 86–99. [2] Mizuno H. and Boss A. P. (1985) *Icarus, 63,* 256–268. [3] Rickman H. (1991) in *Comets in the Post-Halley Era, Vol. 2.,* (R. L. Newburn et al. eds.) Kluwer Academic Publ., Netherlands, 733–760. [4] Yamamoto T. (1985) in *Ices in the Solar System* (J. Klinger et al., eds.) 205–219. [5] Sanford S. A. and Allamandola L. J. (1990) *Icarus, 87,* 188–192.